Introduction

Functions of the Circulatory System:

1) Transportation:

- All of the substances essential for cellular metabolism are transported by the circulatory system.
- These substances can be categorized as follows:
  a) *Respiratory:*
  - Red blood cells, or *erythrocytes,* transport oxygen to the cells. In the lungs, oxygen from the inhaled air attaches to hemoglobin molecules within the erythrocytes and is transported to the cells for aerobic respiration.
  - Carbon dioxide produced by cell respiration is carried by the blood to the lungs for elimination in the exhaled air.

  b) *Nutritive:*
  - The digestive system is responsible for the mechanical and chemical breakdown of food so that it can be absorbed through the intestinal wall into the blood and lymphatic vessels.
  - The blood then carries these absorbed products of digestion through the liver to the cells of the body.

  c) *Excretory:*
  - Metabolic wastes (such as urea), excess water and ions, and other molecules not needed by the body are carried by the blood to the kidneys and excreted in the urine.

2) Regulation:

- The circulatory system contributes to both hormonal and temperature regulation.
  a) *Hormonal:*
  - The blood carries hormones from their site of origin to distant target tissues where they perform a variety of regulatory functions.

  b) *Temperature:*
  - Temperature regulation is aided by the diversion of blood from deeper to more superficial cutaneous vessels or vice versa.
  - When the ambient temperature is high, diversion of blood from deep to superficial vessels helps cool the body; when the ambient temperature is low, the diversion of blood from superficial to deeper vessels helps keep the body warm.

3) Protection:

- The circulatory system protects against blood loss from injury and against pathogens, including foreign microbes and toxins introduced into the body.
  a) *Clotting:*
  - The clotting mechanism protects against blood loss when vessels are damaged.

  b) *Immune:*
  - The immune function of the blood is performed by the leukocytes (white blood cells) that protect against many disease-causing agents (pathogens).

Component of the Circulatory System:

➢ *The heart:*

- Is a four-chambered double pump.
- Its pumping action creates the pressure needed to push blood through the vessels to the lungs and body cells.
- Like all liquids, blood flows down a pressure gradient from an area of higher pressure to an area of lower pressure
- At rest, the heart of an adult pumps about 5 liters of blood per minute. At this rate, it takes about 1 minute for blood to be circulated to the most distal extremity and back to the heart.

➢ *Blood vessels:*

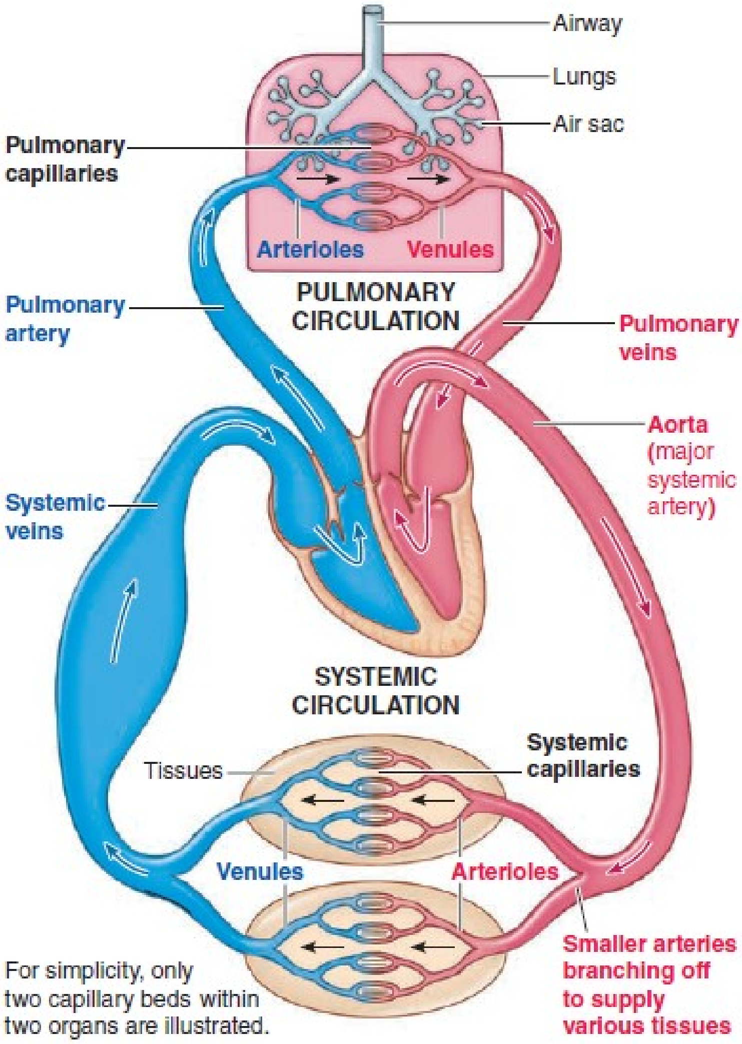
- Form a tubular network that permits blood to flow from the heart to all the living cells of the body and then back to the heart.
- Arteries carry blood away from the heart, whereas *veins* return blood to the heart. Arteries and veins are continuous with each other through smaller blood vessels.

➢ *Blood:*

- It is the transport medium within which materials being transported long distances in the body, such as oxygen (O_2), carbon dioxide (CO_2), nutrients, wastes, electrolytes and hormones.

Basic Organization of the Cardiovascular System:

- Arteries progressively branch as they carry blood from the heart to the organs. A separate small arterial branch delivers blood to each of the various organs. As a small artery enters the organ it is supplying, it branches into arterioles, which further branch into an extensive network of capillaries. The capillaries rejoin to form venules, which further unite to form small veins that leave the organ. The small veins progressively merge as they carry blood back to the heart.
- Blood travels continuously through the circulatory system to and from the heart through two separate vascular (blood vessel) loops, both originating and terminating at the heart (as shown in the figure).
- The systemic circulation is a circuit of vessels carrying blood between the heart and all body systems except the lungs, it is also called the greater circulation or peripheral circulation.
- The pulmonary circulation consists of a closed loop of vessels carrying blood between the heart and the lungs (pulmo means "lung"); it is also called the lesser circulation.



Basic organization of the cardiovascular system

Blood Cycle within the Circulatory System:

- Arteries branch extensively to form a “tree” of progressively smaller vessels. The smallest of the arteries are called arterioles.
- Blood passes from the arterial to the venous system in microscopic capillaries, which are the thinnest and most numerous of the blood vessels.
- All exchanges of fluid, nutrients, and wastes between the blood and tissues occur across the walls of capillaries.
- Blood flows through capillaries into microscopic veins called venules, which deliver blood into progressively larger veins that eventually return the blood to the heart.
- If all of the vessels in the body were strung end to end, they could circle the circumference of Earth twice.

Physical Laws Governing Blood Flow

Definition:

- Blood flow is the amount of blood that passes through a certain vessel/unit time (L/min).

Estimation of Blood Flow:

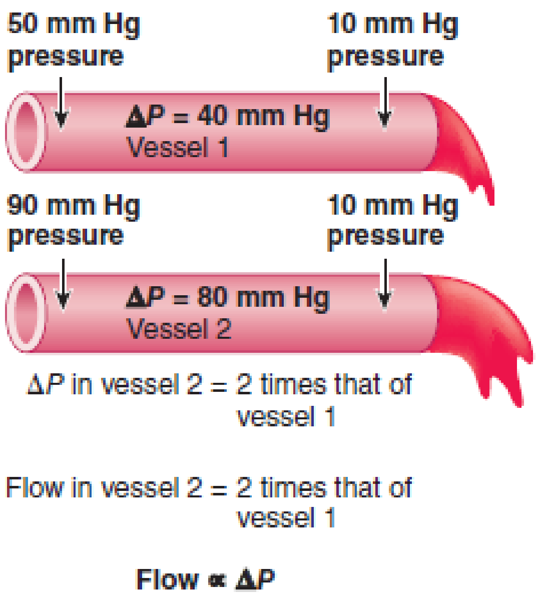
- Total blood flow in the circulatory system (= **C**ardiac **O**ut**P**ut "COP") or even the flow through a specific organ, could be estimated as follow:
  1) Measurement:
     a) *Direct*.
        - Invasive method by cannculating the blood vessel.
     b) *Indirect*:
        - Non invasive method.
        - Using different devices applied to the outside of the vessel to measure flow.
        - They are called *"flowmeters"*.
  2) Calculation:
        - Using *Ohm's law* as follows:

$$\textit{Flow (F) = Pressure gradient } (\Delta P) \textit{ / Resistance (R)}$$
$$F = \Delta P / R$$

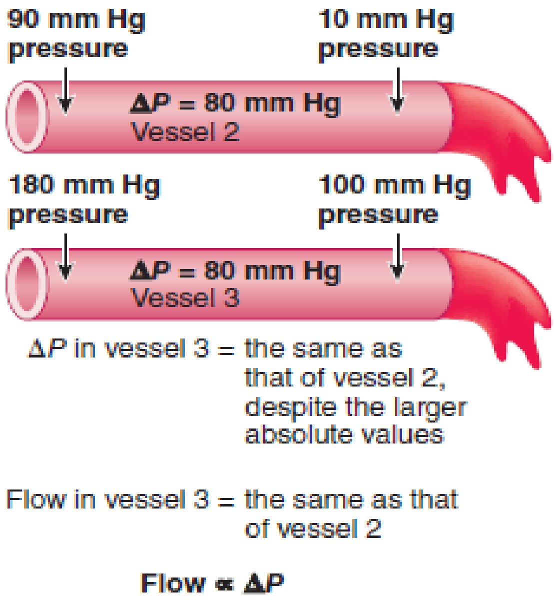
Major Determinants of Blood Flow:

1) Pressure gradient (ΔP):

- Blood flow is directly proportionate to the pressure gradient (ΔP).
- Pressure gradient is the difference in pressure between the beginning and the end of a vessel.
- The pressure gradient is important than absolute pressure in controlling blood flow.
- Blood flows from an area of higher pressure to an area of lower pressure down a pressure gradient. The greater the pressure gradient forcing blood through a vessel, the greater the flow rate through that vessel.
- Contraction of the heart imparts pressure to the blood, which is the main driving force for flow through a vessel.
- ↑ Blood pressure → ↑ Flow by:
  - ↑ Force that pushes the blood forward.
  - Distend the vessels.



(a)
Comparison of flow rate in vessels with a different ΔP



(b)
Comparison of flow rate in vessels with the same ΔP

Relationship of flow to the pressure gradient in a vessel;

(a): As the difference in pressure (ΔP) between the two ends of a vessel increases, the flow rate increases proportionately.

(b): Flow rate is determined by the difference in pressure between the two ends of a vessel, not the magnitude of the pressures at each end.

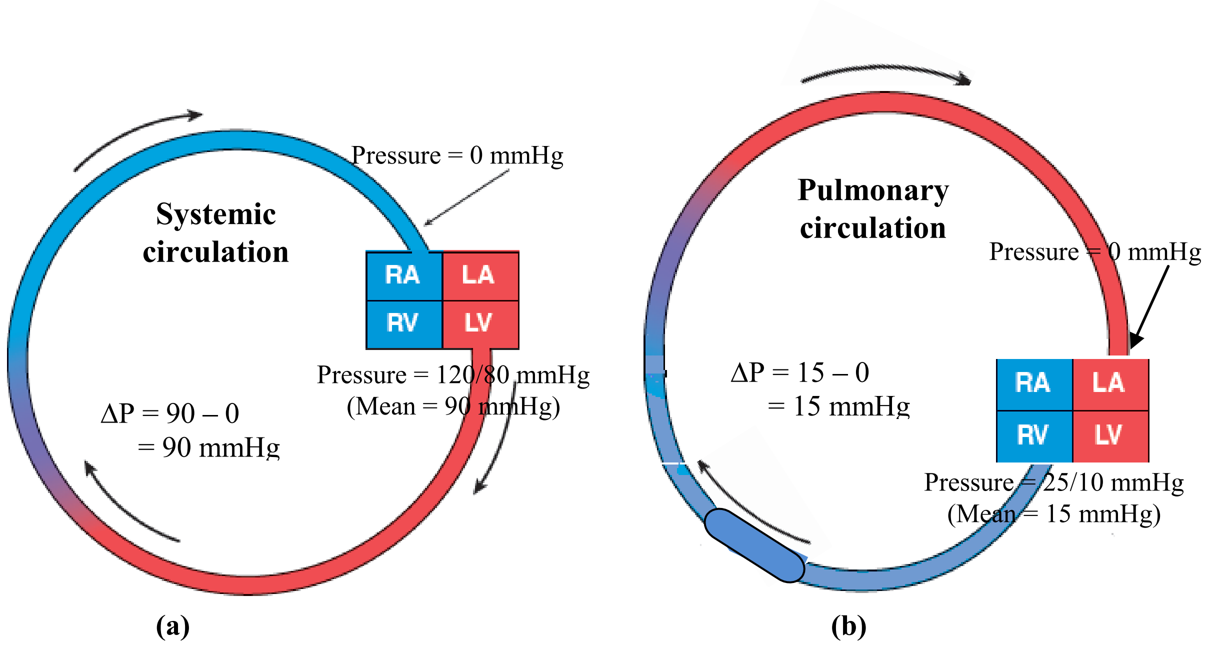
☺ Pressure gradient across the systemic & pulmonary circulations:

➢ ΔP across SYSTEMIC circulation:

- If the systemic circulation is pictured as a single tube leading from and back to the heart (as shown in the figure), blood flow through this system would occur as a result of the pressure difference between the beginning of the tube (the aorta) and the end of the tube (the junction of the venae cavae with the right atrium).
- The average pressure, or **M**ean **A**rterial **P**ressure (MAP), is about 90 mmHg; the pressure at the right atrium (RAP) is 0 mmHg.
- The "pressure gradient", or driving force (ΔP), is therefore about 90 – 0 = 90 mmHg.

➢ ΔP across PULMONARY circulation:

- Similarly, the pulmonary circulation starts from- and back to the heart, blood flow would occur as a result of the pressure difference between the beginning of the tube (the pulmonary artery) and the end of the tube (the left atrium).
- The average pressure, or **M**ean **P**ulmonary **P**ressure (MPP), is about 15 mmHg; the pressure at the left atrium (LAP) is 0 mmHg.
- The "pressure gradient", or driving force (ΔP), is therefore about 15 – 0 = 15 mmHg.



Blood flow is produced by a pressure difference;

(a): The flow of blood in the systemic circulation is ultimately dependent on the pressure difference (ΔP) between the mean pressure of about 90 mmHg at the origin of flow in the aorta and the pressure at the end of the circuit 0 mmHg in the vena cava, where it joins the right atrium (RA).

(b): The flow of blood in the pulmonary circulation is dependent on the pressure difference (ΔP) between the mean pulmonary pressure of about 15 mmHg at the origin of flow in the pulmonary artery and the pressure at the end of the circuit 0 mmHg in the left atrium (LA).

(RV = right ventricle; LV = left ventricle).

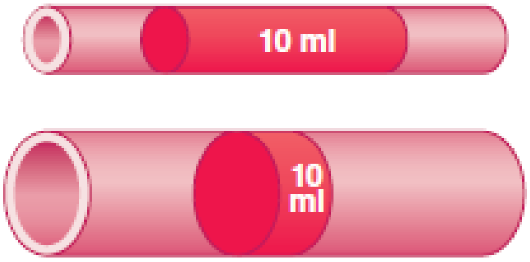
2) <u>Resistance (R)</u>:

- Blood flow is inversely proportionate to the resistance (R).
- Resistance is the impedance to blood flow in a vessel.
- As resistance to flow increases, it is more difficult for blood to pass through the vessel, so flow rate decreases (as long as the pressure gradient remains unchanged).
- When resistance increases, the pressure gradient must increase correspondingly to maintain the same flow rate. Accordingly, when the vessels offer more resistance to flow, the heart must work harder to maintain adequate circulation.
- *Resistance results from*:
  1) Frictional forces between the blood & the wall of the vessel.
  2) Frictional forces between the blood molecules.
- *Determinants of vascular resistance*:
  1) Viscosity of the blood (direct relation).
  2) Vessel length (direct relation).
  3) Vessel radius (inverse relation).

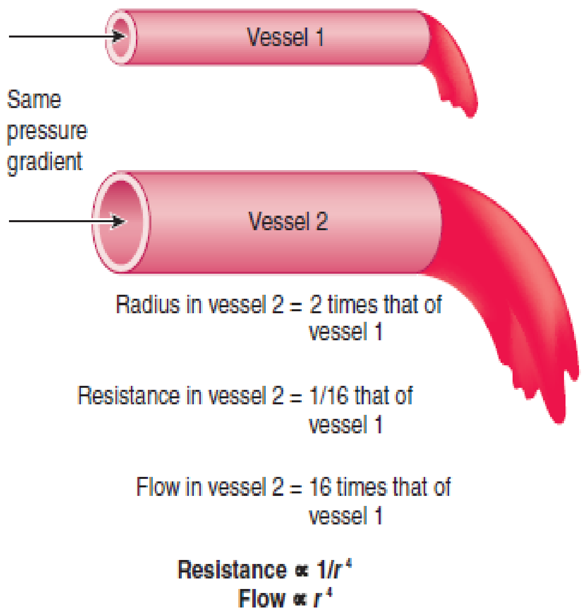
$$\text{Resistance (R)} \propto \text{viscosity } (\eta) \times \text{length (L)} \times 1/\text{radius (r)}$$

- *Viscosity*:
  - Viscosity refers to the friction developed between the molecules of a fluid as they slide over each other during flow of the fluid.
  - The thicker a liquid is, the greater its viscosity, the greater the resistance to flow.
  - Viscosity of normal blood is about three times as great as the viscosity of water.
  - Blood viscosity is determined primarily by the number of circulating red blood cells (= hematocrit value).
  - Normally, this factor is relatively constant and not important in controlling resistance. Occasionally, blood viscosity and resistance to flow are increased because an excessive number of red blood cells are present (e.g., polycythemia), in this case blood flow is more sluggish than normal.
  - Other factors that affect blood viscosity are the plasma protein concentration and types of proteins in the plasma, but these effects are so much less than the effect of hematocrit that they are not significant considerations in most hemodynamic studies.
- *Radius*:
  - It is the principle factor controlling vascular resistance.
  - Because blood "rubs" against the lining of the vessels as it flows, the greater the vessel surface area in contact with the blood, the greater the resistance to flow. Surface area is determined by both the length and the radius of the vessel. At a constant radius, the longer the vessel is, the greater the surface area and the greater the resistance to flow. Because vessel length remains constant in the body, it is not a variable factor in the control of vascular resistance.
  - Thus, the major determinant of resistance to flow is the vessels radius.
  - Fluid passes more readily through a large vessel than through a smaller vessel.
  - The reason is that a given volume of blood comes into contact with more of the surface area of a small-radius vessel than of a larger-radius vessel, resulting in greater resistance.
  - Furthermore, a slight change in the radius of a vessel brings about a notable change in flow because; the resistance is inversely proportional to the fourth power of the radius (multiplying the radius by itself four times).

$$\text{Resistance (R)} = 8L\eta / \pi r^4$$



(a)
Comparison of contact of a given volume of blood with the surface area of a small-radius vessel and a large-radius vessel



(b)
Influence of vessel radius on resistance and flow

Relationship of resistance and flow to the vessel radius;

(a): The smaller-radius vessel offers more resistance to blood flow because the blood "rubs" against a larger surface area.

(b): Doubling the radius decreases the resistance to 1/16 and increases the flow 16 times because the resistance is inversely proportional to the fourth power of the radius.

☺ Resistance in the systemic & pulmonary vascular beds:

- The vascular resistance in the pulmonary circulation is far less than the systemic circulation.
- This is because the pulmonary vessels are: short, wide diameter, with scanty muscle fibers in their wall and weak neuronal control (refer to your lecture).

Regulation of Tissue Blood Flow:

- Poiseuille's–Hagen law illustrates all the factors contribute to blood flow:

$$\text{Flow (F)} = \Delta P \times \pi r^4 / 8L\eta$$

- However, blood flow is ultimately regulated by 2 factors:
  1) Pressure gradient (ΔP).
  2) Radius of the vessel (r).
- Importantly, the radius of arterioles can be regulated and is the key factor in controlling resistance to blood flow throughout the vascular circuit.
- Thus, the volume of blood flowing through an organ can be adjusted by regulating the caliber (internal diameter) of the organ's arterioles.
- *Vasoconstriction* (VC):

- Is the term refers to narrowing of a vessel.
- It is due to smooth muscle layer contraction.
- This contraction leads to reduction in vessel's circumference and its radius becomes smaller.
- Thus increasing resistance and decreasing flow through that vessel.

- *Vasodilatation* (VD):
    - Is the term refers to enlargement in the circumference and radius of a vessel as a result of its smooth muscle layer relaxation.
    - Vasodilatation leads to decreased resistance and increased flow through that vessel.
- At a given pressure gradient, blood can be diverted from one organ to another by variations in the degree of vasoconstriction and vasodilatation of arterioles (that is, by variations in vessel radius, r). Vasoconstriction in one organ and vasodilatation in another result in a diversion, or shunting, of blood to the second organ.
- Because arterioles are the smallest arteries and can become narrower by vasoconstriction, they provide the greatest resistance to blood flow. Blood flow to an organ is thus largely determined by the degree of vasoconstriction or vasodilatation of its arterioles.
- So, the rate of blood flow to an organ can be increased by dilation of its arterioles and can be decreased by constriction of its arterioles.
- The arteriolar radius is regulated by neuronal, hormonal & local factors (refer to your lecture).

☹- Use Poiseuille's–Hagen law to differentiate between the systemic & pulmonary circulations regarding: blood flow, pressure gradient & vascular resistance.

Types of Resistance in the Circulatory System

Resistance in Series & Parallel Vascular Circuits:

➢ Series circuits:

- Blood pumped by the heart flows from the high-pressure part of the systemic circulation (i.e., aorta) to the low-pressure side (i.e., vena cava) through many miles of blood vessels arranged in series and in parallel.
- The arteries, arterioles, capillaries, venules, and veins are collectively arranged in series.
- When blood vessels are arranged in series, flow through each blood vessel is the same and the total resistance to blood flow (R_{Total}) is equal to the sum of the resistances of each vessel:

$$R_{Total} = R_1 + R_2 + R_3 + R_4 \ldots$$

- The total peripheral vascular resistance is therefore equal to the sum of resistances of the arteries, arterioles, capillaries, venules, and veins.

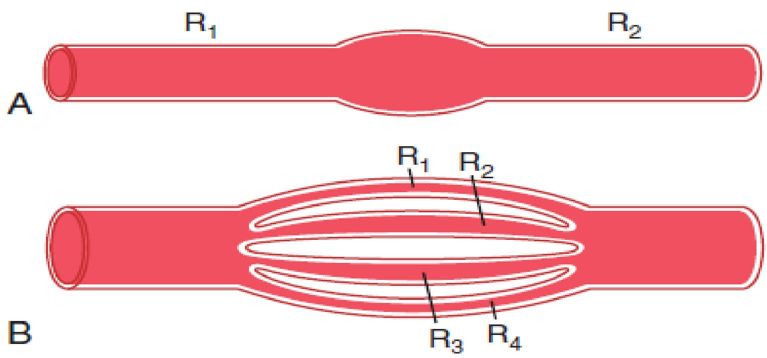
- In series circuits the blood flow passes from one organ to another.

➢ Parallel circuits:

- Blood vessels branch extensively to form parallel circuits that supply blood to the many organs and tissues of the body.
- This parallel arrangement permits each tissue to regulate its own blood flow, to a great extent, independently of flow to other tissues.
- For blood vessels arranged in parallel, the total resistance to blood flow is expressed as:

$$1/R_{Total} = 1/R_1 + 1/R_2 + 1/R_3 + 1/R_4 \ldots.$$

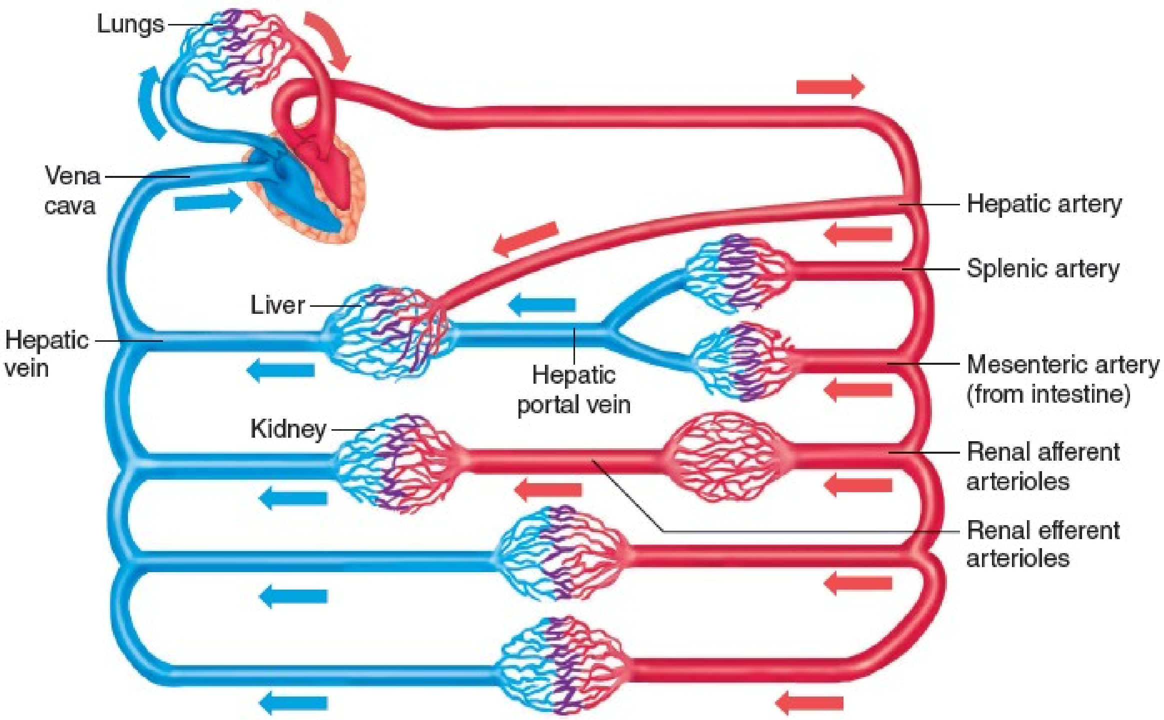
- It is obvious that for a given pressure gradient, far greater amounts of blood will flow through this parallel system than through any of the individual blood vessels. This is because; the total resistance is far less than the resistance of any single blood vessel.
- Flow through each of the parallel vessels is determined by the pressure gradient and its own resistance, not the resistance of the other parallel blood vessels. However, increasing the resistance of any of the blood vessels increases the total vascular resistance.
- Presence of many parallel blood vessels makes it easier for blood to flow through the circuit because each parallel vessel provides another pathway for blood flow.
- For example, brain, kidney, muscle, gastrointestinal, skin, and coronary circulations are arranged in parallel. Blood flow through each tissue is a fraction of the total blood flow (cardiac output) and is determined by the resistance for blood flow in the tissue, as well as the pressure gradient.
- This arrangement ensures that all organs receive blood of the same composition that is; one organ does not receive "leftover" blood that has passed through another organ. Because of this parallel arrangement, blood flow through each organ can be independently adjusted as needed.



Vascular resistances (R): in series **(A)** and in parallel **(B)**.

Comparison between Series & Parallel Vascular Circuits

	Series Circuits	Parallel Circuits
Resistance	- High - Equal to the sum of resistances in all vessels passing through	- Low - Equal to the resistance in that vessel only
Blood Flow:		
a- Quantity	The same in all tissues passing through	Its own share
b- Quality	Less oxygen content (leftover)	Pure arterial (high oxygen content)
c- Control	Dependent on other tissues	Highly adjusted (independent)



Blood flow in series & in parallel circuits of the vascular system.

☺- What is meant by total peripheral resistance (TPR)?

- It is the sum of the resistances in all blood vessels within the systemic circulation.
- It is affected by VC or VD anywhere in the vascular system.
- The arteries that supply blood to the organs are generally in parallel rather than in series with each other (with few exceptions). That is, arterial blood passes through only one set of resistance vessels (arterioles) before returning to the heart.

☠☹💣 **Clinical Application:**

It is important to know that amputation of a limb or surgical removal of a kidney will remove a parallel circuit and thus, reduces the blood flow while increasing total peripheral vascular resistance.

Velocity of Blood Flow

- Velocity is the displacement of blood per unit time.
- It could be calculated according to the following formula:

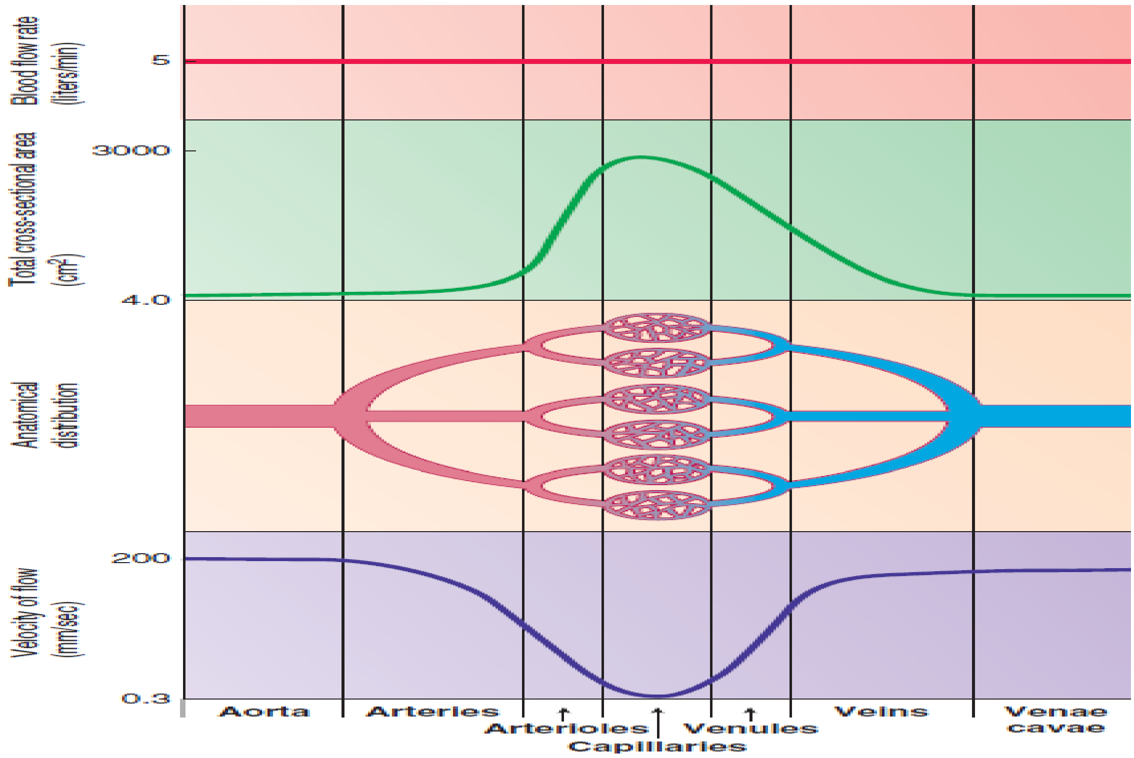
Velocity (V) = Flow of blood (F) / Total **C**ross **S**ectional **A**rea (CSA)

$$V = F / CSA$$

- *Total cross sectional area*:
  - It represents the diameters of all vessels of the same type, put side by side.
  - The average velocity of fluid movement at any point in a system of tubes in parallel is inversely proportional to the total cross-sectional area at that point.
  - Therefore, the average velocity of the blood is high in the aorta, declines steadily in the smaller vessels, and is lowest in the capillaries, which have 1000 times the total cross-sectional area of the aorta.
  - The average velocity of blood flow increases again as the blood enters the veins and is relatively high in the vena cava, although not so high as in the aorta.
- *Measurement of velocity*:
  - Systemic circulation:
    - Clinically, the velocity of blood flow in the systemic circulation can be measured by injecting a bile salt preparation into an arm vein and timing the first appearance of the bitter taste it produces.
    - This technique is called "arm-to-tongue" circulation.
    - The average normal time is 15 seconds.
  - Pulmonary circulation:
    - By a similar way, the velocity of blood flow in the pulmonary circulation can be measured by injecting ether into an arm vein and timing the first appearance of the smell of ether in the subject's breath is produced.
    - This technique is called "arm-to-lung" circulation.
    - The average normal time is 15 seconds.

Vessel	Total Cross Sectional Area (CSA, cm^2)
- Aorta	2.5
- Small arteries	20
- Arterioles	40

- Capillaries	2500
- Venules	250
- Small veins	80
- Venae cavae	8



Total cross sectional area and its relation to blood flow velocity

☺ **N.B.:**

☞ It is important to distinguish between velocity, which is displacement per unit time (e.g., cm/s), and flow, which is volume per unit time (e.g., cm^3/s).

☞ The cross-sectional area of the veins is much larger than those of the arteries, averaging about four times those of the corresponding arteries. This difference explains the large blood storage capacity of the venous system in comparison with the arterial system.